Canadian National Report
for the 10th WMO/UNEP Ozone Research Managers Meeting
Geneva, 28-30 March 2017

1. OBSERVATIONAL ACTIVITIES

1.1 Column measurements of ozone

Both the Canadian Brewer Spectrophotometer Network and the Canadian Ozonesonde Network are operational with no major changes to the two programs.

The Canadian Brewer Spectrophotometer Network consists of eight main observing sites, monitoring total column ozone and spectral ultraviolet radiation (UV). Each of the network's mid-latitude stations (Saturna Island, British Columbia; Stony Plain, Alberta; Churchill, Manitoba; Toronto, Ontario; and Goose Bay, Newfoundland and Labrador) operate two Brewer spectrophotometers, and each Arctic station (Resolute, Eureka and Alert in Nunavut) have three instruments on-site. The additional instruments provide redundancy; minimize operational downtime, and thus, reduce likelihood of long gaps in the data due to logistical difficulties (transportation of goods, and technician travel time for repairs) associated with monitoring in the Canadian Arctic. They also provide means of optimizing the observations of both column ozone and UV spectral irradiance; and are for quality assurance purposes. Since the 1990s, Environment and Climate Change Canada has been replacing the single monochromator spectrophotometers with double monochromator instruments through network lifecycle management. Currently, one double monochromator Brewer spectrophotometer is operating per station. The advantage of using double monochromator Brewers is the expansion of the daily hours of data collection by also including low sun conditions, particularly important for the winter, spring and autumn observations from the Canadian Arctic. All Canadian stations have been visited for service, upgrade and calibration in the 2014-2017 time period, meeting a two-year cycle maintenance target. Two new double Mark III Brewers were acquired in 2017 as part of the formal lifecycle management program, and their performance is currently under evaluation.

Canada, in collaboration with the U.S. National Oceanic and Atmospheric Administration (NOAA), maintains two Brewer spectrophotometers (one single and one double) at the Mauna Loa Observatory in Hawaii and one instrument at South Pole station in the Antarctic. Data from the South Pole Brewer are submitted to the WMO and are used in the WMO Antarctic Ozone Bulletins. There is a continuous record for the South Pole station since 2008. In 2015, the Brewer instrument at the station was replaced with a newly calibrated one. Other Brewers have been operated by Canadian universities for research purposes in collaboration with Environment and Climate Change Canada, for which data were not reported on a regular basis.

Total column ozone and UV data are made available through the World Meteorological Organization (WMO) World Ozone and Ultraviolet Radiation Data Centre (WOUDC).

Since 2013, Environment and Climate Change Canada has acquired six Pandora spectral sunphotometers. The instrument not only measures nitrogen dioxide (NO_2) and sulphur dioxide (SO_2), but also is capable of producing high quality total column ozone data. A Pandora instrument was compared with the Brewer Triads (single and double monochromator instruments) to assess its suitability for long-term ozone monitoring (Zhao et al. 2016).

1.2 Profile measurements of ozone

Environment and Climate Change Canada launches ozonesondes at eight locations across Canada (Kelowna, British Columbia; Stony Plain, Alberta; Churchill, Manitoba; Goose Bay, Newfoundland and Labrador; Yarmouth, Nova Scotia; and Resolute, Eureka and Alert in Nunavut) on a weekly basis using electrochemical concentration cell ozonesondes. A limited number of higher frequency launches were carried out during Match campaigns (in collaboration with the Alfred Wagner Institute in Bremerhaven, Germany) and Atmospheric Chemistry Experiment (ACE) validation campaigns.

Ozonesonde data are archived in the WMO WOUDC.

1.3 UV measurements

1.3.1 Broadband measurements and narrowband filter instruments

Currently, broadband observations are not made by Environment and Climate Change Canada; however, commercial forecasting companies have developed their own broadband UV network for observing erythemal-weighted UV at major Canadian cities. Also, the United States Department of Agriculture (USDA)'s UV-B Monitoring and Research Program (UVMRP) is co-located with the Canadian Brewer spectrophotometers at the monitoring site in Toronto. As part of their measurement program, the UVMRP obtains erythemal-weighted UV-B irradiance using a Yankee Environmental Systems UVB-1 pyranometer. Further information on UVMRP can be found at: http://uvb.nrel.colostate.edu/UVB/index.jsf.

In summer 2015, Environment and Climate Change Canada conducted a project associated with the 2015 Toronto Pan American and Para-Pan American Games. As part of this project, four Kipp and Zonen broadband instruments that measure erythemal UV provided diurnal monitoring during the Games in addition to the measurements from the Brewer instruments in Toronto.

1.3.2 Spectroradiometers

Observations of spectral UV-irradiance are made using Brewer spectrophotometers. Approximately five UV spectra are obtained each hour. All eight Brewer sites are equipped with double Brewer spectrophotometers that measure UV in the 286-363 nm spectral range (the older Mark II Brewer instruments take measurements in the 290-325 nm range). Collected data are used for UV index forecast validation purposes.

1.4 Calibration activities

The Triad of absolutely calibrated double monochromator Brewer instruments (#145, #187 and #191) was established in addition to the existing Triad of single monochromator Brewer spectrophotometers (#008, #014 and #015). As part of the Brewer World Calibration Centre (WCC) activities, three Brewer Triad instruments (#008, #145 and #187) were absolutely calibrated at Mauna Loa Observatory in October 2015. The next calibration of Triad instruments at the Mauna Loa Observatory will be carried out in August 2017.

Following the WMO Ozone SAG recommendation, Toronto Brewer #145 was sent to Izana, Spain to compare the Triad of the Brewer World Calibration Centre (WCC) situated in Toronto with the Triad of the Regional Brewer Calibration Center for Europe (RBCC-E) in Spain in March 2014. The intercomparison between the reference instruments of the two calibration centres was completed by the end of May 2014.

Environment and Climate Change Canada’s Brewer #017 is recognized by WMO as the global traveling standard instrument. It has been used for more than 30 years and is directly linked to the global stratospheric monitoring program coordinated by WMO. Ozone calibrations have been transferred from the WCC Triad in Toronto to instruments in various countries with the travelling standard instrument. Also, calibration of the RBCC-E Triad to the WCC Triad has been established by yearly comparison with the travelling standard Brewer #017.

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

2.1 Ozonesonde records re-evaluation

The Canadian ozonesonde record was re-evaluated for measurements of the vertical distribution of ozone over Canada from 1966 to 2013, and the results was published in 2016 (Tarasick et al. 2016). The re-evaluation corrected a number of minor systematic errors, resulting in reduced scatter and drift in the comparison with total ozone measurements. A new error analysis finds that Canadian ozonesondes are now close to 5% overall error.

2.2 Pandora spectrometers and Brewer Triad

Environment and Climate Change Canada is testing and evaluating a new instrumentation, the Pandora spectrometer. The instrument measures the ultraviolet-visible solar spectra used to retrieve total columns of atmospheric trace gases. From the spectral measurements, total column of NO_2, SO_2, ozone and other species can be obtained. The measurement modes are Direct Sun, sky (scattered) light, and Direct Moon. It is designed for satellite validation and pollution monitoring. Since 2013, two Pandora instruments are deployed at monitoring sites, one in Toronto and the other in Fort McKay within the oil sands region. There are plans to deploy more instruments across Canada.

The performance of the Pandora spectrometer was evaluated for total ozone column from a comparison with the Brewer Triads in Toronto. The goal was to evaluate the instrument for its suitability for long-term monitoring of total ozone column. The results show the Pandora instrument’s accuracy and precision of total ozone column measurements are comparable with those for the Brewer Triad in Toronto (Zhao et al. 2016). Its precision is similar or even better than that for the Brewer instrument; however, there is a large dependence on stratospheric temperature for which has to be accounted.

2.3 Satellites (space-based monitoring and research)

The OSIRIS (Optical Spectrograph and Infrared Imager System), a Canadian instrument on Odin satellite since 2001, measures spectra of limb scattered sunlight from the ultraviolet to the near-infrared that are primarily used to retrieve ozone, NO_2 and aerosol extinction. The instrument has 2-km vertical resolution and good accuracy and long-term stability with respect to altitude registration. The instrument continues to operate in 2017.

Launched in August 2003 for a two-year mission, the SCISAT/ACE (Atmospheric Chemistry Experiment) satellite continues to perform very well. The instruments and satellites are functioning nominally with only minor degradation in performance, which will not limit continued operations. There are two instruments: the infrared ACE- Fourier Transform Spectrometer (FTS) produces profiles of nearly 60 different species and isotopologues, and the MAESTRO focuses in visible-near infrared for ozone, NO_2 and water vapour. The SCISAT/ACE is in a highly-inclined orbit that was chosen as the initial focus of the mission was on polar ozone chemistry. This mission has expanded and currently SCISAT/ACE contributes to studies related to ozone recovery and chemistry, climate science and air pollutants. The broad range of species from the ACE-FTS allows a more complete picture of ozone loss, and provides attribution of changes with measurements of a wide range of chlorine species (sources, breakdown products and reservoirs). The vertical resolution of ACE-FTS is approximately 3 km (from field-of-view), and of MAESTRO is about 1.5 km. One example of results is from recent validation comparisons for ozone (and other species), which show excellent performance of ACE-FTS compared to MLS on the National Aeronautics and Space Administration (NASA)'s Aura satellite and MIPAS on European Space Agency (ESA)'s Envisat satellite.

The on-going validation of ozone profiles from the ACE-FTS and OSIRIS satellite instruments is being performed using measurements from PEARL.

Environment and Climate Change Canada is making use of SCISAT/ACE measurements to assess the quality of stratospheric ozone model predictions, which is a central component of the next version of Canada's UV forecasting system.

2.4 Polar Environment Atmospheric Research Laboratory (PEARL)

The Polar Environment Atmospheric Research Laboratory (PEARL) is a Canadian Network for the Detection of Atmospheric Change (CANDAC) facility for atmospheric research in the Arctic. It began measurements in 2005-2006 and continues to carry out research on large range of atmospheric constituents including the partial and total column measurements of trace gases. The PEARL instrument suite is being used to examine trends in halogen containing species and other atmospheric constituents / parameters that control the ozone budget. These measurements are being used to quantify the contributions from dynamics, chemistry, and climate change to stratospheric ozone depletion and recovery, and to study the tropospheric ozone budget. PEARL-based observations have been used to validate SCISAT/ACE and Odin/OSIRIS data. Over the past few years, the Ozone Differential Adsorption Lidar (DIAL) at PEARL was refurbished, and made measurements in winter/spring 2017 as part of the Canadian Arctic ACE/OSIRIS Validation Campaign. Other instrumentation includes UV-visible and Fourier transform infrared (FTIR) spectrometers that measure ozone and related species (e.g., hydrochloric acid, hydrofluoric acid, chlorofluorocarbons, bromine oxide). The UV-VIS and FTIR data are contributed to the Network for the Detection of Atmospheric Composition Change (NDACC – see ftp://ftp.cpc.ncep.noaa.gov/ndacc/station/eureka/hdf/ftir/ and ftp://ftp.cpc.ncep.noaa.gov/ndacc/station/eureka/ames/uvvis/). Bromine explosions and tropospheric ozone depletion events are regularly observed at PEARL in the springtime, most recently in March 2017 (K. Walker and K .Strong, private communication 2017). A combination of surface ozone analyzer and UV-spectrometer data is being used to characterize this event as well as using ozonesondes and complementary measurements by other instruments. PEARL data are being utilized for validation, scientific studies, instrument development and demonstration. PEARL is a very well used and equipped facility, and will be part of the validation program for the upcoming TROPOMI (TROPOspheric Monitoring Instrument) mission on ESA's Sentinel-5 Precursor.

2.5 The University of Toronto Atmospheric Observatory (TAO)

The University of Toronto Atmospheric Observatory (TAO) houses a Bomem DA8 high-resolution Fourier transform infrared spectrometer that has been operational since 2002. This instrument acquires solar infrared absorption spectra for long-term measurements of stratospheric and tropospheric trace gases. The TAO FTIR is an NDACC instrument and regularly measures ozone (see ftp://ftp.cpc.ncep.noaa.gov/ndacc/station/toronto/hdf/ftir/). TAO data have contributed to validation of ACE-FTS, SCIAMACHY, and OSIRIS, the first detection of NO in the mesosphere and lower thermosphere using ground-based FTIR spectroscopy, and studies of chlorine trends, polar intrusions, and tropospheric transport of pollutants over Toronto. TAO will be part of the validation program for TROPOMI.

3. THEORY, MODELLING, AND OTHER OZONE RELATED RESEARCH

3.1 Stratospheric ozone related modelling

The Canadian Middle Atmosphere Model (CMAM) is a chemistry-climate model that has been developed jointly by Environment and Climate Change Canada and university-based collaborators over almost two decades. The latest version of CMAM, with an improved representation of tropospheric chemistry, will be used to provide simulations requested for the Chemistry Climate Model Initiative (CCMI), which is providing new CCM simulations for the 2018 Scientific Assessment of Ozone Depletion.

3.2 Chemical data assimilation

Chemical data assimilation consists of improving chemical model forecasts by incorporation of information from constituent observations, including ozone measurements. Global stratospheric and column ozone data assimilation is being conducted at Environment and Climate Change Canada as a means to investigate different aspects for improving or inquiring insight in chemical data assimilation, to investigate feedback effects on weather, and to providing lateral boundary conditions for regional chemical data assimilation and improving ultraviolet (UV) index forecasts. Some of these activities involve international collaborations such as undergoing activities with the Belgium Institute for Space Aeronomy (BIRA). With the assimilation system, stratospheric ozone forecasts are generated from the LINearized stratospheric OZone chemistry model (LINOZ) of McLinden et al. (2000) which has been incorporated in the Global Environmental Multiscale (GEM) weather prediction model. These efforts are contributing to the development of a comprehensive system for assimilating air quality measurements (including stratospheric ozone) into Environment and Climate Change Canada's air quality model prediction systems

3.3 New UV index prediction project

The original UV index forecast was developed 25 years ago by scientists at Environment and Climate Change Canada. It is being updated. The new UV index forecasts make direct use of:

- Ozone model forecasts at Numerical Weather Prediction (NWP) resolution.
- Satellite measurements of ozone through data assimilation.
- Solar UV fluxes at the surface provided by the Environment and Climate Change Canada's Global Environmental Multiscale (GEM) model to calculate clear-sky and all-sky UV indices.

There will allow for new products such as daytime variation (e.g., hourly); longer forecasts (e.g., four days or more); and global, continental and regional maps. This new UV index forecasting system is integrated tightly to the current weather forecasting system. Also, the system is to automatically take advantage of improvements in global and regional cloud/precipitation forecasts using GEM irradiances. The goal is for operational implementation of the new UV index forecasting system in 2018-19.

As part of a new UV index forecasting and interactive ozone-radiation project, a multi-sensor ozone assimilation project with total column bias correction was undertaken. The assimilated data sets include OMI, GOME2 of MetOp A&B, and OMPS-NM total column ozone retrieved from the TOMS algorithm and OMPS-NP and SBUV/2 partial column profiles. The selected standard is the OMI with validation using Brewer data. The project will be completed in 2017.

The Toronto 2015 Pan American and Para-Pan American Games were used to demonstrate the new UV Index forecast. New Kipp and Zonen UV sensors were installed at four locations across the Games footprint in southern Ontario's Greater Golden Horseshoe Area. They are in addition to the Brewer instruments in Toronto. UV index model forecasts provided 4-day hourly forecast maps updated twice a day. The evaluation study of UV index forecasts is expected to be completed in 2017.

4. DISSEMINATION OF RESULTS

4.1 Data reporting

Brewer ozone and UV data are available in near real-time, and used for various applications. They are produced as hourly bulletins for UV index forecasts, and used for satellite data validation. Brewer data also are used in WMO Arctic and Antarctic Ozone Bulletins, NOAA Arctic Report Cards, the Bulletin American Meteorological (BAMS) State of the Climate reports and other publications.

Total column ozone and ozonesondes data from the Canadian measurement programs are submitted to the WMO WOUDC.

The WOUDC (woudc.org) is operated by the Meteorological Service of Canada at Environment and Climate Change Canada. It has been renewed to create a new foundation to meet growing requirements. The system renewal has been operational since March 2015. The ultimate goal of the renewal is to enhance the data submission mechanism and infrastructure; to provide effective and efficient data management; to modernize data access mechanisms and improve accessibility and usability of the website. In addition, focus on standards and interoperability has been a key driver of the renewal.

Key enhancements to the WOUDC are as follows:

- Near-real time data (OzoneSonde, TotalOzone) – They are of known quality, but not fully quality-controlled. The paradigm is to 'Release early, release often'.
- Validation services – Format validation and quality assessment tools are available for online use.
- Self-serve metrics/reporting. They are available to the Ozone and UV Scientific Advisory Groups (password protected).
- New dataset – RocketSonde datasets were added in 2016.
- NetCDF data delivery – It is available to address modelling community requirements, thus lowering the barrier to integration/workflows.
- Integrated distributed Data Centre search (NDACC, Eubrewnet) – It is for searching remote data centres directly from WOUDC, and downloading from an authoritative data centre.
- Level 0 data archive
- Standards (ISO, OGC) – Interoperability is a key driver of WMO, Open Data, GEOSS (Global Earth Observation System of Systems) and beyond. Standards lower the barrier and extend the reach and usability of the data for existing and new communities.
- Geospatial capabilities – Online maps and data is now GIS capable.
- WMO alignment (WIS, GAW, WIGOS) – WMO provides a next generation system aligned with key WMO drivers

UV-VIS and FTIR data from PEARL, and FTIR data from TAO are archived on the NDACC database (http://www.ndsc.ncep.noaa.gov/).

4.2 Information to the public

Canada provides daily UV index forecasts through the Meteorological Service of Canada regular weather reports on http://weather.gc.ca/canada_e.html, and daily UV Index Forecast public text bulletins https://weather.gc.ca/forecast/public_bulletins_e.html/. The 1-day forecast, provided when the UV index value is 3 or higher, consists of the midday UV index accounting for average cloud conditions from 10 am to 4 pm over 900 locations in Canada.

Each year, based on springtime ozone levels, a summer seasonal forecast is provided to the public through the Environment and Climate Change Canada website: https://www.ec.gc.ca/uv/default.asp?lang=En&n=396B9A58-1#X-201701131108212. The forecast normally comes out before Canada's Victoria Day long weekend as this is the 'first' long weekend of summer in Canada and many individuals are prone to extended hours outdoors for the first time since winter.

Private sector forecasts of the UV index are also provided by organizations such as the Weather Network:
http://www.theweathernetwork.com/uvreport/canuv_en/?ref=topnav_homepage_uvrepo

4.3 Relevant scientific papers

Environment and Climate Change Canada will contribute to the upcoming 2018 WMO/UNEP Scientific Assessment of Ozone Depletion.

Ozone and UV-related reports are as follows:

- 2014 WMO/UNEP Scientific Assessment of Ozone Depletion
- NOAA Arctic Report Cards
- BAMS State of Climate reports

Scientific publications from 2014-2017 are as follows:

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5. PROJECTS, COLLABORATION, TWINNING AND CAPACITY BUILDING

The following are selected collaborative projects:

- CAFTON - the Canadian FTIR Observing Network, a Canadian Space Agency-funded project http://www.atmosp.physics.utoronto.ca/CAFTON/.

- PAHA (Probing the Atmosphere of the High Arctic) project with three themes, one of which is Composition Measurements (CM), which includes a project on Ozone and Related Species (CM-O3) , which is funded by the National Science Research Council of Canada. http://www.candac.ca/candacweb/content/paha.

- Collaboration in the development of the 4DVar/EnsKF systems at the Belgium Institute for Space Aeronomy (BIRA, Belgium; on-going).

- Contribution to "Study group on the added-value of chemical data assimilation in the stratosphere and upper-troposphere" in collaboration with BIRA and other institutions. This study (2013-2015) was supported by the International Space Science Institute (ISSI), Switzerland, through the International Teams in Space and Earth Sciences program. http://www.issibern.ch/teams/dataassimsphere/.

6. IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 9th OZONE RESEARCH MANAGERS MEETING

Systematic observations are ongoing, especially ground-based sites with long records and in the Arctic region. All Dobson/Brewer and ozonesondes sites open in the 1950s and 1960s are operational. Environment and Climate Change Canada, within its resources, continues to work on improving the measurements of ozone and UV radiation, which includes any technical issues related to instrument performance and analysis of data collected in the Brewer network. The testing and evaluation of the Pandora spectrometer continue for remote sensing of atmospheric composition.

The new UV index forecast system based on ozone data assimilation is being tested and evaluated, with its implementation in the near future. Modelling studies are ongoing to improve our understanding of the relationship between ozone and climate. Although Odin/OSIRIS and SCISAT/ACE are beyond their design life, they continue to operate successfully, and thus, research related to their measurements continue unabated.

In 2015, Canada renewed its commitment to the sponsorship of the WMO Brewer Trust Fund for another five years from April 1, 2015 to March 31, 2020. This fund provides $37,500 CAN per year to support the development of Brewer observations through instrument calibrations and capacity building.

7. FUTURE PLANS

One of the main future applications of Environment and Climate Change Canada's ground-based remote sensing network, which includes ozone monitoring, is validation of satellite measurements of atmospheric composition related to air quality and stratospheric ozone. The satellite validation activities relate to TROPOMI and NASA's TEMPO (Tropospheric Emissions: Monitoring Pollution) mission as follows:

- Validation of NO_2, SO_2, formaldehyde, and perhaps other species using new Pandora instruments, which assures the quality of satellite data over Canada.
- Validation of ozone and UV index products using the Canadian Brewer Spectrophotometer Network as well as Environment and Climate Change Canada's ozone data assimilation output and UV index forecasts.
- Validation of ozone profiles using ozonesonde measurements from Canadian stations to ensure satellite tropospheric ozone measurements are suitable for Environment and Climate Change Canada's Air Quality Health Index (AQHI) applications (assimilation, validation, research, trend studies, etc.)
- Validation of aerosol optical depth (AOD) data products using Canadian AERONET measurements and possibly Environment and Climate Change Canada aerosol data assimilation output from the AQHI forecasting system.